Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t911751996

Model estimates of runoff in the closed, semiarid Estancia basin, central New Mexico, USA / Estimations par simulation de l'écoulement dans le bassin endoréique semi-aride d'Estancia, Nouveau Mexique central, états-Unis

K.M. MENKING[a]; K.H. SYED[b]; R.Y. ANDERSON[c]; N.G. SHAFIKE[d]; J.G. ARNOLD[e]
[a] Department of Geology and Geography, Vassar College, Poughkeepsie, New York, USA [b] Biological Sciences, University of Lethbridge, Alberta, Canada [c] Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico, USA [d] New Mexico Interstate Stream Commission, Albuquerque, New Mexico, USA [e] United States Department of Agriculture, Agricultural Research Service, Temple, Texas, USA

Online publication date: 19 January 2010

To cite this Article MENKING, K.M. , SYED, K.H. , ANDERSON, R.Y. , SHAFIKE, N.G. and ARNOLD, J.G.(2003) 'Model estimates of runoff in the closed, semiarid Estancia basin, central New Mexico, USA / Estimations par simulation de l'écoulement dans le bassin endoréique semi-aride d'Estancia, Nouveau Mexique central, états-Unis', Hydrological Sciences Journal, 48: 6, 953 — 970

To link to this Article: DOI: 10.1623/hysj.48.6.953.51424

URL: http://dx.doi.org/10.1623/hysj.48.6.953.51424

Model estimates of runoff in the closed, semiarid Estancia basin, central New Mexico, USA

K. M. MENKING
Department of Geology and Geography, Box 59, Vassar College, Poughkeepsie, New York 12604, USA
kimenking@vassar.edu

K. H. SYED
Biological Sciences, 4401 University Drive W, University of Lethbridge, Lethbridge, Alberta T1K 3M4, Canada

R. Y. ANDERSON
Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131, USA

N. G. SHAFIKE
New Mexico Interstate Stream Commission, 121 Tijeras NE, Suite 2000, Albuquerque, New Mexico 87106, USA

J. G. ARNOLD
United States Department of Agriculture - Agricultural Research Service, 808 East Blackland Road, Temple, Texas 76502, USA

Abstract The 5000 km^2 topographically closed Estancia basin in central New Mexico has been the focus of several palaeoclimatic studies based on changes in the level of late Pleistocene Lake Estancia. A large, unknown volume of surface runoff and groundwater from adjacent mountains contributed to the hydrological balance during highstands and lowstands. The US Department of Agriculture hydrological model SWAT (Soil and Water Assessment Tool) and the US Geological Survey groundwater flow model MODFLOW, with the LAK2 package, were used in this study to estimate runoff and water balance under present climate. A Geographic Information Systems (GIS) interface was used for SWAT, digitized data were applied for soils and vegetation, and limited streamflow data were used to obtain an approximate calibration for the model. Simulated streamflow is generally within 30% of observed values, and simulated runoff for the entire basin is about 8% of the annual inflow volume needed to support lowstands of the former Lake Estancia. Results from the combined models suggest application to other palaeoclimate investigations in semiarid lake basins.

Key words runoff; Soil and Water Assessment Tool (SWAT); MODFLOW; LAK2 package; Estancia basin, New Mexico, USA

Estimations par simulation de l'écoulement dans le bassin endoréique semi-aride d'Estancia, Nouveau Mexique central, États-Unis

Résumé Le bassin endoréique d'Estancia dans le centre du Nouveau Mexique, d'une superficie de 5000 km^2, a été au centre de plusieurs études paléoclimatiques basées sur les changements de niveau du lac Estancia du Pléistocène tardif. Un grand volume, inconnu, d'eaux de surface et d'eaux souterraines provenant des montagnes adjacentes a contribué au bilan hydrologique pendant les états de hautes et de basses eaux. Le modèle hydrologique SWAT (outil d'évaluation du sol et de l'eau) du ministère de l'agriculture des Etats-Unis et le modèle d'écoulement souterrain MODFLOW du service géologique des Etats-Unis, enrichi du module LAK2, ont été utilisés pour estimer l'écoulement et le bilan hydrologique sous le climat actuel. Nous avons utilisé

Open for discussion until 1 June 2004

une interface de SWAT sous Système d'Informations Géographiques. Nous avons utilisé des données digitalisées pour les sols et la végétation, et des données d'écoulement en nombre limité pour obtenir un calage approximatif du modèle. L'écoulement simulé en cours d'eau est généralement dans une fourchette de 30% autour des valeurs observées, et l'écoulement simulé pour l'ensemble du bassin correspond à environ 8% du volume annuel d'alimentation du lac nécessaire pour soutenir les états de basses eaux de l'ancien lac Estancia. Les résultats des modèles combinés suggèrent une application à d'autres investigations paléoclimatiques dans des bassins de lac en milieu semi-aride.

Mots clefs écoulement; SWAT; MODFLOW; module LAK2; bassin d'Estancia, Nouveau Mexique, États Unis

INTRODUCTION

Some of the best geological records of climatic change are preserved as shorelines and sediments in closed-basin lakes that are, or were supported by, runoff from mountainous drainage basins. Such lakes were widely distributed in the southwestern United States during the late Pleistocene, but are now either dry or greatly diminished in extent (Smith & Street-Perrott, 1983). The volume and surface area of these lakes are highly responsive to changes in energy inputs, precipitation, and runoff, but the potential of closed-basin lakes to provide quantitative estimates of past climate change has been limited by several factors. For example, many hydrological models needed to simulate inflow to these lakes are event-based and operate on time steps inappropriate for simulating responses to long term changes in climate. Likewise, mountainous and arid to semiarid drainage basins commonly lack streamflow and weather data necessary for model calibration, and mountain hydrology reflects complex associations with lateral and vertical gradients in precipitation, temperature, soils, and vegetation. Because of these limiting factors, only very general estimates (examples include Leopold, 1951; Benson & Paillet, 1989; Smith & Street-Perrott, 1983) of late Pleistocene and Holocene runoff have been attempted, and much uncertainty remains about the past changes in precipitation and other climatic variables responsible for the repeated and abrupt changes in lake level documented in the geological record (Bradley, 1999).

Recently, runoff models that operate on a daily time step have been employed to estimate water resources under future global change scenarios (Fontaine *et al.*, 2001; Rosenberg *et al.*, 1999; Stone *et al.*, 2001; Stonefelt *et al.*, 2000). Such models have potential utility in palaeoclimatic studies as their long time step makes them appropriate for the simulations necessary to study past changes in lake level. Furthermore, at least one of these models, the US Department of Agriculture (USDA) Soil and Water Assessment Tool (SWAT), is a physically-based model developed to use readily available weather data and digital data sets for topography, land cover, and soils, allowing it to operate in drainage basins for which calibration data are limited or lacking (Neitsch *et al.*, 2002).

This study reports on estimates of modern runoff for the hydrologically closed, 5000 km^2 Estancia basin in central New Mexico that were derived using the SWAT model. A large pluvial lake occupied the basin and experienced extreme fluctuations in size throughout the late Pleistocene (Fig. 1; Allen & Anderson, 2000). The climatic conditions leading to Lake Estancia highstands have been a matter of considerable debate, resulting in a wide range of estimates for Pleistocene precipitation and

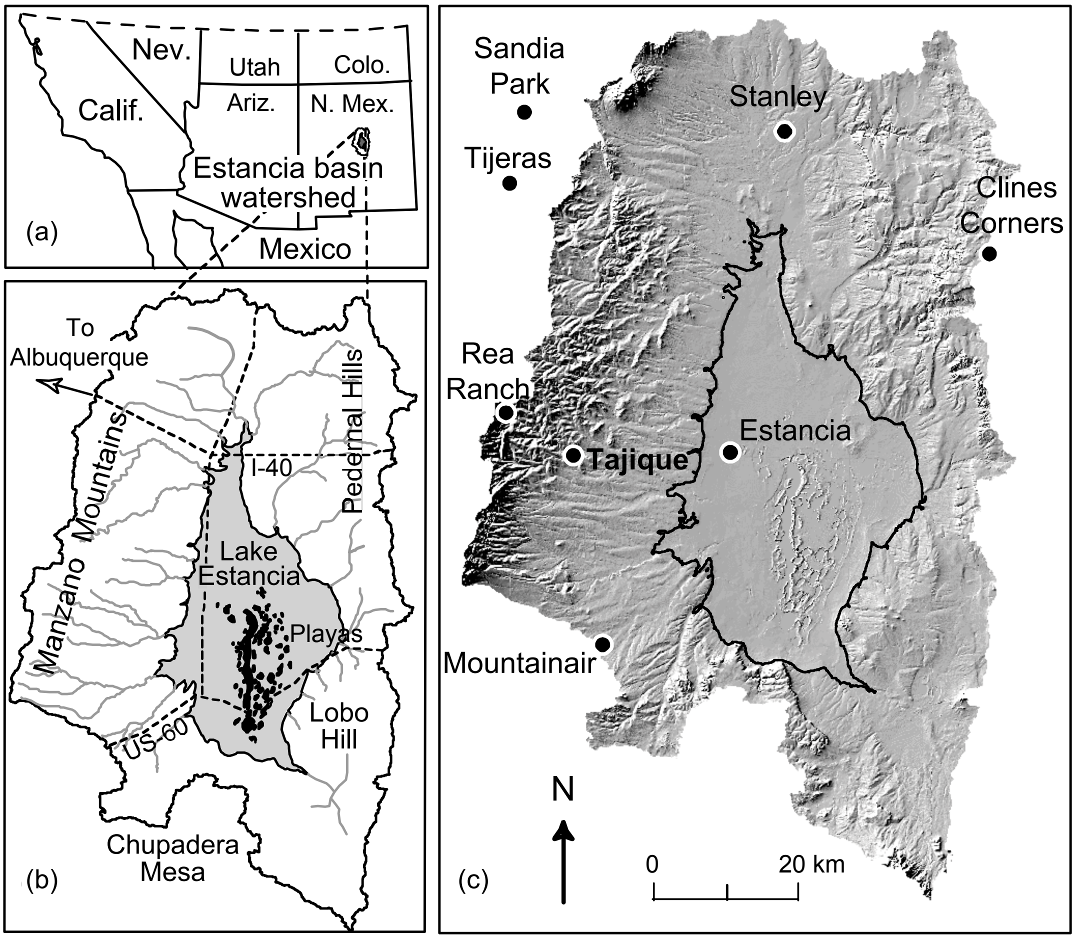

Fig. 1 (a) Location of the Estancia basin in the southwestern United States. (b) Estancia drainage basin, principal stream channels (note centripetal pattern), and maximum area of the Lake Estancia highstand (1890 m, shaded). (c) Relief map of the Estancia drainage basin showing location of weather stations. Highest elevations are above 3000 m in the southern Manzano Mountains. The nearly flat valley floor is bounded by the 1890-m highstand, (solid line) and is underlain by late Pleistocene lake sediment. Discharge of groundwater is through numerous deflation basins cut by wind into the valley floor, at ~1855 m. Wet playas in deflation basins (see (b)) are outlined by dunes of pelletized clay that rise up to 30 m above the valley floor.

temperature in southwestern North America (Leopold, 1951; Antevs, 1954; Galloway, 1970; Brakenridge, 1978).

Like other mountainous drainage basins in the American Southwest, the Estancia basin has been the site of few streamflow measurements. However, some early interest in the basin, related to homesteading, resulted in the establishment of a temporary weather station (Rea Ranch) near the crest of the adjacent Manzano Mountains (Fig. 1(c)) and measurements of total monthly streamflow nearby. The daily weather records were used along with topographic, soil, and land cover information to simulate streamflow under historical conditions with the SWAT model, and the results were compared to the measured streamflow data obtained from the archives of the New Mexico State Engineer.

In this paper, the setting of the Estancia basin, discretization of the topography into SWAT model sub-basins and channels, comparison of measured and simulated flow values in the Manzanos, and total runoff estimates for the basin are described. Although meteorological and streamflow data are sparse, they represent the kinds of data commonly available in mountainous and arid to semiarid regions and, as will be demonstrated, appear sufficient to allow estimates of modern runoff. Ultimately, it is intended to use the model to explore previously proposed late Pleistocene climate scenarios. As a first step toward this goal, the SWAT estimate of annual runoff is combined with previous estimates of groundwater flow (Shafike & Flanigan, 1999), and the MODFLOW-LAK2 package (Council, 1999) is employed to assess the modern hydrological balance of the Estancia basin.

STUDY SETTING

The Estancia basin lies approximately 100 km southeast of Albuquerque, New Mexico in the southwestern USA (Fig. 1). The drainage divide on the west follows the crest of the Manzano Mountains, with two elevations exceeding 3000 m and much of the ridge crest above 2800 m, lowering to ~2500 m toward the north. The northern and eastern divides rise to ~2100 and 2200 m, and the southern part of the basin is bounded by an escarpment with an elevation of ~2000 m. The average elevation of the valley floor measures 1855 m, and the southern half is dissected to depths of 10 m by a single elongated deflation basin ~19 km long and by more than 80 smaller deflation basins about 1 km in diameter, most of which contain wet playas.

Surface hydrology

Surface drainage within the Estancia basin is toward the centre from all sides (Fig. 1(b)). Today, only sub-basins that drain the highest peaks in the Manzano Mountains produce perennial streams, and nearly all surface flow infiltrates into the subsurface before reaching the valley floor. Only during precipitation events associated with summer convective thunderstorms of unusual intensity, or during exceptionally large spring snowmelt events, does runoff originating in the Manzano Mountains reach the edge of the valley floor. In contrast to the modern semiarid setting, during the late Pleistocene many small centripetal streams discharged directly into pluvial Lake Estancia, which rose and fell at least nine times between 24 and 12 ^{14}C k.y. BP (radiocarbon kiloyears (millennia) before present) (Allen & Anderson, 2000). Most stream channels terminate at an elevation of ~1890 m, the elevation of the lake's highest shorelines, and some larger channels reach the 1875 m elevation of a younger and lower, ~10 ^{14}C k.y. BP highstand.

Nearly continuous records of total monthly streamflow are available between August 1915 and September 1919 (Neel, 1925) for a few sub-basins along the upper slopes of the Manzano Mountains (see also Fig. 3(a)). These include Cañon de Tajique (48.1 km^2), Cañon de Torreon (41.7 km^2), Cañon Nuevo (12.5 km^2), and Cañon de Piños Reales (11.3 km^2). All of these drainage basins extend to the range crest and were gauged at elevations near 2000 m. Attempts to locate the daily measurements upon which these monthly values were based were unsuccessful, and little is known about the methods used in measuring streamflow. Nevertheless, the monthly flow totals prove valuable for comparison to the simulated runoff.

In addition to the monthly flow measurements, gain and loss measurements were made on Tajique Creek and Torreon Creek for three days in 1985 and 1987, demonstrating that streams are effluent from the crest of the Manzanos down to an elevation of ~2000 m, below which they turn influent (White, 1994). The only other streamflow monitoring conducted in the Estancia basin has been the measurement, since the mid 1980s, of peak annual discharge on six streams located throughout the basin (Beal & Gold, 1987, 1988).

The office of the State Engineer undertook a reconnaissance study of surface water resources in the Estancia basin that estimated a total annual flow of $\sim 7.5 \times 10^6$ m^3 $year^{-1}$ for streams draining the southern end of the Manzano Mountains (New Mexico State Engineer, 1961; values reported in acre-ft $year^{-1}$). Their study was conducted using the Gallinas River basin (60 km northeast of the Estancia basin) as an analogue for the southern Manzanos, and by reducing average Gallinas River flow over a 14-year period ($\sim 1.0 \times 10^7$ m^3 $year^{-1}$) by ~25% to represent the intermittent nature of flow from the Manzanos. Under this scenario, annual Manzano Mountain runoff was estimated to measure $\sim 3.2 \times 10^4$ m^3 per km^2 of drainage area (75% of 4.3×10^4 m^3 km^{-2} determined for Gallinas River).

Groundwater

Groundwater flow is toward the centre of the Estancia basin, and virtually all sub-surface flow is discharged to the atmosphere through the surfaces of playas that occupy the deflation basins (Shafike & Flanigan, 1999). Recharge is largely through karstic limestone and clastic sedimentary rocks that form the upper slopes of the Manzano Mountains along most of their length (Allen, 1993). Above ~2200 m these formations are overlain by very shallow to deep, stony and non-stony loams (Bourlier *et al.*, 1970). The lower foothills of the Manzanos, between ~2000 and 2200 m, are covered by deep, moderately coarse- to moderately fine-textured loams. A second area of groundwater recharge occurs between ~2000 and ~1890 m, where Tertiary and Quaternary alluvium up to 120 m in thickness underlies the valley floor, forming a narrow, highly permeable zone around the basin into which streams draining the Manzanos infiltrate (White, 1994). The Quaternary alluvium below 1890 m is overlain by lakebeds of marly clay and gypsum.

Climate

Precipitation falling on the Estancia basin shows strong orographic dependence (Fig. 2(a)). On average, the valley floor receives about 350 mm of annual precipitation (measurements from the Estancia weather station—Fig. 1(c)). At 2030 m elevation (Tajique station—Fig. 1(c)), that value has increased to 460 mm, and the highest peaks of the Manzano Mountains receive over 750 mm $year^{-1}$ (Local Climatological Data (NOAA); Tuan *et al.*, 1973). Seasonal precipitation strongly reflects different moisture sources. Between December and March, about 33% of annual moisture is brought to the high elevations and slopes of the Manzanos by storms that originate in the Pacific and follow a southerly path across the continent. July and August thunderstorms

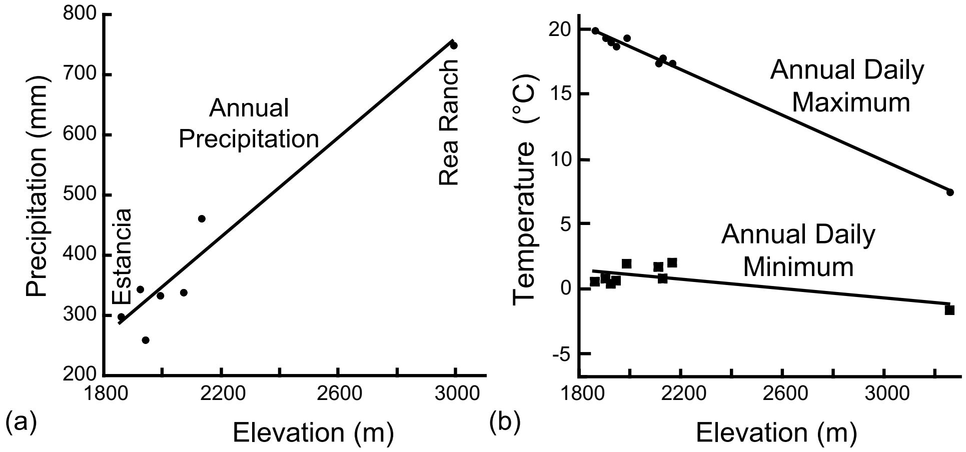

Fig. 2 Elevation gradient of (a) annual precipitation and (b) annual daily maximum and minimum temperature. Monthly gradients were used with the SWAT model.

produced by the Arizona monsoon contribute an additional 31% of total annual precipitation. Five months during the autumn and spring account for only ~20% of annual moisture, and large storms in October, with moisture originating in the Pacific, may account for as much as 16% of total precipitation.

Average monthly temperatures for the valley floor range from about 0°C in January to 21°C in July, with average annual lapse rates for daily maximum and daily minimum temperature of ~8.8 and ~1.8°C km^{-1} respectively (Fig. 2(b)). Annual evaporation in the playa area has been measured at between ~700 and 950 mm (DeBrine, 1971; Menking *et al.*, 2000). Potential evaporation, derived from pan data for Santa Fe and adjusted to the elevation of the Estancia basin, averages 1200 mm $year^{-1}$ (Leopold, 1951).

Vegetation

Like precipitation and temperature, vegetation in the Estancia basin is strongly influenced by elevation and topography (see also Table 1). A small area (2.6 km^2) of grassland exists at elevations above ~2450 m in the Tajique and Torreon creek drainage basins of the Manzano Mountains (Thompson *et al.*, 1996). Otherwise, elevations greater than ~2150 m generally support conifer forest. Below 2150 m, trees become more widely spaced and are scattered among a grass and shrub assemblage. At elevations below ~1950 m, the slopes are grass-covered, with scattered shrubs.

ADAPTATION OF USDA SWAT MODEL

A surface water runoff model of the Estancia basin was developed using the USDA's SWAT model. SWAT is a physically-based, continuous-time model that operates on a daily time step, and is the continuation of a long-term effort of non-point-source pollution modelling by the USDA Agricultural Research Service (Arnold *et al.*, 1996; Neitsch *et al.*, 2002). The model is designed to operate in large ungauged basins to simulate the impacts of land management practices on the movement of agricultural chemicals and of sediment on hillslopes and in channels, but it can also be used to simulate the response of basins to measured precipitation events.

Fontaine *et al.* (2001), Stone *et al.* (2001) and Stonefelt *et al.* (2000) have used SWAT to simulate the responses of the Spring Creek (South Dakota), Missouri River, and Wind River drainage basins to future climate change resulting from increased greenhouse gas emissions. Like the Estancia basin, these drainage basins contain mountainous topography, experience runoff associated with spring snowmelt, and include a mixture of forest and grassland ecosystems. These studies showed that SWAT is sufficiently sensitive to changes in temperature, precipitation, and atmospheric CO_2 concentration to be useful in predicting runoff under different climatic change scenarios, hence our decision to examine SWAT for use in modelling palaeohydrology.

Model description

The hydrological processes simulated by SWAT are described in detail in Arnold *et al.* (1996) and in Neitsch *et al.* (2002) and include snowmelt, infiltration, lateral subsurface flow, transmission losses, bare ground evaporation, transpiration, groundwater movement, and channel and hillslope routing. In SWAT, the landscape consists of a soil unit (up to 10 different layers are possible) that overlies shallow and deep aquifer units. Hillslopes are represented as planes that route water toward stream channels based on vegetation characteristics and soil properties. The hydrological component of SWAT solves the water balance equation:

$$SW_t = SW + \sum_{i=1}^{t} \left(R_i - Q_i - ET_i - P_i - QR_i \right) \quad (1)$$

where SW is the soil moisture content, SW_t is the soil moisture content at time t, R is daily precipitation, Q is runoff, ET is evapotranspiration, P is percolation, QR is return flow, and the subscripts i and t denote time. The model applies precipitation to the landscape and uses the Green-Ampt Mein-Larson infiltration equation (G-A M-L; Neitsch *et al.*, 2002) or SCS curve numbers (SCS, 1972) to determine the amount of runoff. Comparisons of curve number and the G-A M-L infiltration equation revealed that the curve number approach is adequate for determining runoff, particularly when only daily precipitation values are available as inputs to the model (King *et al.*, 1999), and this relationship was therefore used:

$$Q_i = \frac{\left(R_i - 0.2S \right)^2}{\left(R_i + 0.8S \right)} \quad (2)$$

where S is a retention parameter described by:

$$S = 25.4 \left(\frac{1000}{CN} - 10 \right) \quad (3)$$

and CN is the curve number (Neitsch *et al.*, 2002). High values of curve number, associated with bare soils and high clay contents, result in high runoff volumes. The converse is true for low curve number values, which are associated with vegetated and sandier soils.

Potential evaporation can be determined by three different methods. In this study a modified version of the method of Hargreaves & Samani (1985) was used that requires daily maximum and minimum air temperatures as inputs. Once potential evaporation is determined, the model further calculates values of actual soil evaporation, based on the area of bare ground exposed, and of transpiration, based on the leaf area index of the vegetation (*ET*).

Percolation (*P*) is determined from the soil water content at the beginning and end of the daily time step and from the travel time of water through each soil layer, which is dependent on the soil hydraulic conductivity. Return flow (*QR*) of water from the shallow aquifer system to stream channels is calculated from the change in shallow aquifer storage over each time step, and reflects the competing influences of recharge of water to the shallow aquifer by percolation from the overlying soil, the flow of water from the shallow aquifer back to the overlying soil because of evaporative stress, and the percolation of water out of the shallow aquifer into the deep aquifer system. Additional equations calculate mean flow velocity of water in stream channels (Manning equation) and elevation of the water table in the shallow aquifer.

Delineation of drainage sub-basins

This study made use of AVSwat2000 (Di Luzio *et al.*, 2002), an extension built for the Geographic Information Systems software ArcView. The AVSwat2000 model allows the user to delineate sub-basins and stream channels, to overlay soil and land cover information, to input meteorological data, to adjust calibration parameters, and to run the model and view outputs. In ArcView, multiple USGS 30-m digital elevation model (DEM) quadrangles were combined to obtain topographic information for each of the 19 sub-drainage basins (henceforth termed sub-watersheds; Fig. 3(a)) in the Estancia drainage basin, and the composite DEMs were imported into AVSwat2000.

The stream network (Fig. 3(a)) in each sub-watershed was defined by assigning a threshold area of 1000 ha for channel initiation. The selection of threshold area is non-trivial (Bingner *et al.*, 1997), and it was found that it can affect runoff estimates by as much as 15–20%. In a mountainous region, large precipitation–elevation gradients result in reduced simulated precipitation within individual sub-basins for which there is a significant range in elevation. In addition, mountainous areas have large vertical and lateral variations in soils, vegetation, and bedrock geology. For these reasons, runoff is best simulated by a low threshold area, which provides a finely resolved sub-basin and channel network. On the other hand, decreasing the threshold area causes the number of sub-basins to increase geometrically, and thereby greatly increases the amount of data entry required. The value of 1000 ha was selected because it captured most of the lateral and vertical variability while still generating a manageable number of model sub-basins.

Nodes were added to the drainage network to represent the Cañon de Tajique, Cañon de Torreon, Cañon Nuevo, and Cañon de Piños Reales stream gauging stations that operated from 1915 to 1919. Nodes were also placed at the 1890, 1875, and 1862 m elevations of the late Pleistocene Lake Estancia highstand and lowstand shore-lines. Drainage areas (Fig. 3(a)) were drawn with reference to the lowest, 1862 m elevation, and AVSwat2000 delineated the sub-basins in each sub-watershed and

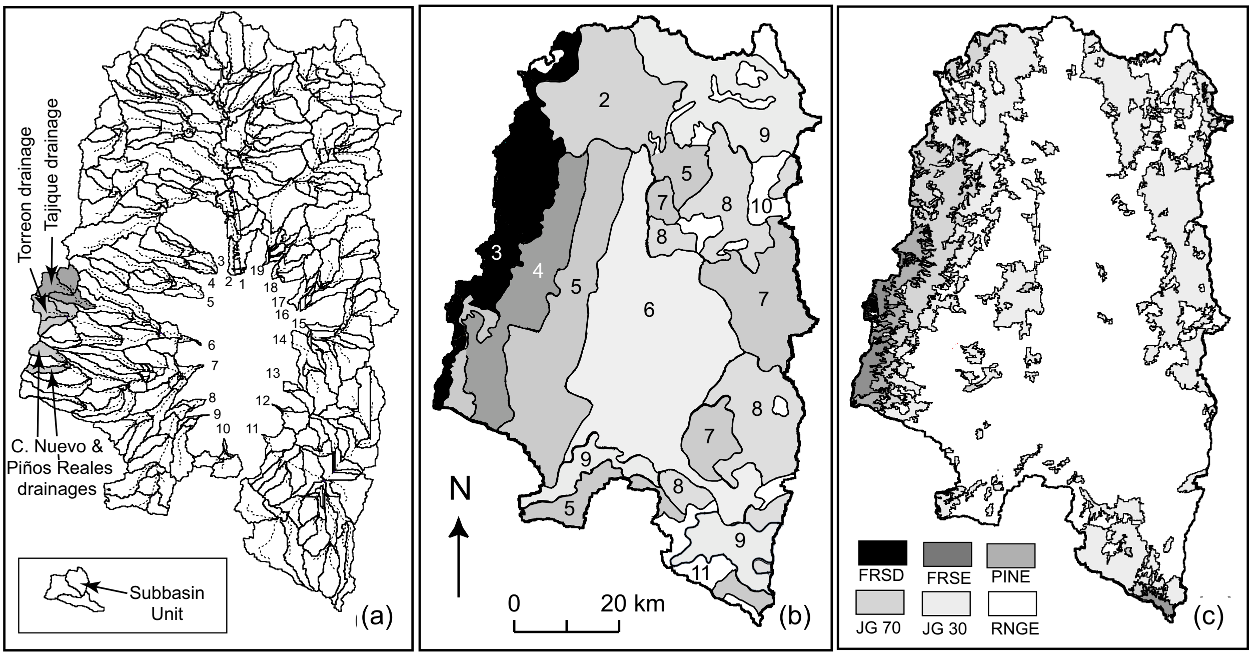

Fig. 3 Distribution of hydrological units, soils, and vegetation in the Estancia basin. (a) Outlets of sub-watersheds are numbered 1–19. Sub-basins with streamflow data are shaded. (b) Major soil types in the Estancia drainage basin. Numbers from soil classification in Bourlier *et al.* (1970). Soils in the west correspond with elevation bands, and consist of shallow to deep, stony and non-stony loams at high elevations grading downward to deep silt loams. (c) Vegetation types used in the SWAT model: FRSD (deciduous forest), FRSE (evergreen forest), PINE (mostly *Pinus ponderosa*), JG70 (mixture of 70% pinyon-juniper and 30% grass), JG30 (mixture of 30% pinyon-juniper and 70% grass), RNGE (grass and desert shrubs).

calculated the sub-basin parameters used to route the runoff, including average slope length, average slope steepness, and length, width, and slope of stream channels. The 19 sub-watersheds contain a total of 330 sub-basins.

Soils and land cover

The STATSGO (State Soil Geographic Database for the Conterminous United States) soils map and database for New Mexico (Fig. 3(b); Thompson *et al.*, 1996) supplied soils information for the model. These data include soil layer thickness, soil texture, available water capacity, saturated hydraulic conductivity, nutrient levels, and organic matter content. Soil properties in the STATSGO database were checked against values in the USDA soil surveys for Torrance (Bourlier *et al.*, 1970) and Santa Fe (Folks, 1975) counties and found to be in general agreement. Where disagreements existed, the values reported in the soil surveys were used in preference to those in the STATSGO database.

Vegetation zones were obtained from the USGS NM-GAP (New Mexico GAP Analysis Project) database (Thompson *et al.*, 1996). Sixteen land cover classes are found in the Estancia basin. Land use/land cover classes used by SWAT are more generalized than those found in the database, and most of the Estancia basin below 2000 m was classified as Range (grassland and mixed grass and shrubland), with higher elevations assigned to Pine, Deciduous Forest, and Evergreen Forest (Fig. 3(c)). Two land cover classes were newly created by combining SWAT's pine and range parameters in order to simulate juniper-grassland assemblages found in the basin.

Individual sub-basins within sub-watersheds were subdivided into hydrological response units (HRUs) based on the soil and land cover combinations found within them. Soils and vegetation types covering less than 10% of the area of each sub-basin were ignored, and dominant types re-proportioned to cover 100% of the sub-basin area. Runoff from each sub-basin was then determined based on a weighted average of the individual HRU runoff values. A total of 1824 HRUs were used in the simulation.

Meteorological data

The SWAT model can either simulate meteorological variables over the entire drainage basin using a "Weather Generator" capability, or the user can specify these values for each sub-basin from instrumental measurements. The Weather Generator uses long-term climate statistics to generate climatic time series. In this study, the Weather Generators for Mountainair, Clines Corners, and Sandia Park, New Mexico (Fig. 1(c)) were used to generate wind speed, relative humidity, and solar radiation. Daily precipitation and daily maximum and minimum temperature values were read from instrumental observations available from the Western Regional Climate Center, Reno, Nevada, and the National Climate Data Center, Asheville, North Carolina, for eight weather stations in and around the Estancia basin (Fig. 1(c)).

Plots of average monthly temperature *vs* station elevation demonstrated near-linear relationships that were used to adjust daily observations of maximum and minimum temperature at a single weather station to the elevations of sub-basins. Precipitation exhibits spatial variations related to local physiography as well as to elevation. Long-term records of precipitation were used to calculate average monthly values of precipitation at each meteorological station. From these values, monthly precipitation *vs* elevation lapse rates were constructed and used in conjunction with daily precipitation values at the meteorological station closest to each individual sub-basin to estimate daily precipitation at the elevation of the sub-basin centroid. For a given day of simulation, if the recorded precipitation at the station gauge closest to the sub-basin centroid was zero, the sub-basin was assigned zero precipitation. If the gauge had recorded precipitation for that day, rainfall was adjusted according to the precipitation–elevation gradient for the relevant month and applied to the sub-basin.

COMPARISON OF OBSERVED AND SIMULATED STREAMFLOWS

True calibration of the SWAT model requires daily streamflow records. While these data are not available for the Estancia basin sub-watersheds, as is the case for many basins of palaeoclimatic interest, monthly summaries of streamflow from 1915 to 1919 are available for several streams along the eastern face of the Manzano Mountains, and provide a basis for comparing observed and simulated flow.

Daily precipitation data from the Rea Ranch Station (USDA Weather Bureau, 1915–1919) were applied over four small drainages (Fig. 3(a)) according to the previously described procedure. Daily maximum and minimum temperature data are not available from the Rea Ranch station, so temperature data from the closest station at the town of Estancia (1862 m) were used, and these values were adjusted to the elevation of sub-basins by using the average monthly lapse rates across the eastern front of the Manzano Mountains.

Monthly streamflow simulation for the Tajique drainage

Initial comparison of measured and simulated streamflow values for Tajique Creek showed that episodes of runoff were clearly related to the season of snowmelt, and that the amount of runoff was determined largely by the total amount of precipitation during the three or four winter months before snowmelt (Fig. 4(a)). Summer monsoon precipitation, although significant, produced little observed or simulated runoff. Snowmelt factors provided in the SWAT model (examples include maximum and minimum melt rates per °C per day and snowmelt temperature) were adjusted to better simulate the timing of snowmelt.

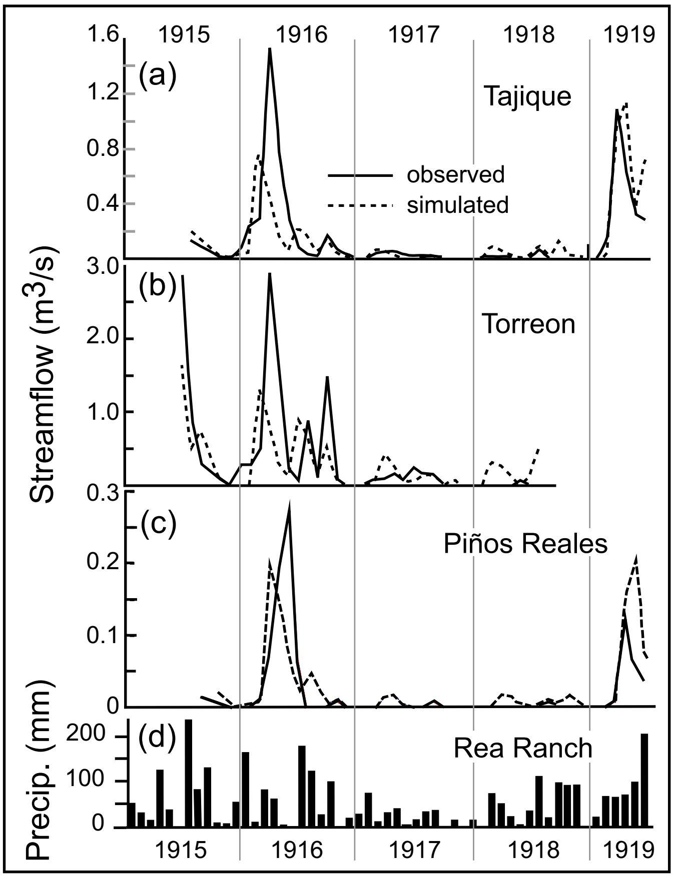

Fig. 4 Monthly observed values of streamflow (solid line) compared with simulated monthly values (dashed line) for (a) Tajique Creek, (b) Torreon Creek, and (c) Cañon de Piños Reales. (d) Precipitation measured at Rea Ranch Station from January 1915 to July 1919. The high flow values in 1916 seen in (a), (b), and (c) followed high precipitation associated with a strong El Niño winter of 1915–1916. Note that simulated water yield tends to underestimate streamflow during wet years, and to overestimate streamflow during dry years (e.g. 1918).

Comparison of total observed and simulated streamflow values from the Tajique sub-watershed, which contained the station at Rea Ranch, shows that the simple linear interpolation of daily precipitation, based on the observed precipitation/elevation gradient, and the regional projection of daily maximum and minimum temperatures from the Estancia weather station provide modelled streamflow values similar to actual monthly values. An exception is the month of extremely high streamflow observed during April 1916, which is underestimated by the model. In addition, the simulation tends to overestimate streamflow during the relatively dry year of 1918. The monthly differences between observed and simulated values tend to cancel each other over several years, and for the entire four-year interval, simulated runoff (1.60×10^7 m^3) is within 4% of observed streamflow (1.66×10^7 m^3).

Comparison of simulations for other sub-watersheds

The same records of precipitation and temperature, and the same factors for vegetation growth, snowmelt, and soil and hydrological conditions at Tajique were applied to the slightly smaller drainage basin of Cañon de Torreon, south of and adjacent to the Tajique drainage basin and farther from the station at Rea Ranch (Fig. 3(a)). In this case, streamflow data are available from August 1915 to August 1918, with the exception of October 1915 when no measurements were made. The simulation for the Torreon drainage (Fig. 4(b)) underestimates runoff by ~25% over the three-year period (total observed runoff: 3.6×10^7 m^3, simulated runoff: 2.7×10^7 m^3). If flow values for Tajique Creek are examined for this same shorter time interval, SWAT underestimates streamflow by about the same amount (28%).

The pattern of seasonal streamflow in the still smaller sub-basin of Cañon de Piños Reales is similar to that of Tajique Creek, with both streams responding to the large runoff events of 1916 and 1919 associated with high winter precipitation (Fig. 4(a) and (c)). However, unlike Tajique Creek, total simulated streamflow for Piños Reales is 25% greater than observed streamflow over the period of record (2.3×10^6 m^3 *vs* simulated runoff of 2.9×10^6 m^3). Another small watershed, Cañon Nuevo, also responds with high streamflow during the spring snowmelts of 1916 and 1919, but simulated values greatly over-represent streamflow during the intervening dry years of 1917 and 1918 (total observed runoff for the period of record is 1.4×10^7 m^3, simulated runoff: 5.4×10^6 m^3). The STATSGO soil map assigns rocky soils to both Cañon de Piños Reales and Cañon Nuevo, and experiments with dominant soil type show that runoff may be overestimated in small, rocky drainage basins.

TOTAL RUNOFF FROM THE ESTANCIA DRAINAGE BASIN

Estimates of runoff for the entire Estancia basin under modern climatic conditions were obtained by routing precipitation and surface runoff through all 19 sub-watersheds. A model run based on overlapping meteorological records for the years 1940–1980 estimates average annual streamflow delivered to the basin floor at an elevation of 1862 m to be 3.9×10^7 m^3 year^{-1}. No measurements of total streamflow in the Estancia basin have ever been made, so it is difficult to assess the validity of this result. However, using the office of the New Mexico State Engineer (1961) estimate for surface flow in the southern Manzanos of ~3.2×10^4 m^3 per km^2 of drainage area yields a value of 3.0×10^7 m^3 $year^{-1}$ when applied to the area of the entire Manzano Mountain range (~930 km^2). This is about 30% greater than the value predicted by SWAT for the same area (~2.1×10^7 m^3 $year^{-1}$). Considering the scarcity of data for comparison with model results, the spatial variability of precipitation, and the assumptions in the estimate made by the State Engineer study (see Introduction), these two independent estimates of total Manzano streamflow along the east face of the Manzano Mountains are in general agreement.

LIMITS ON RUNOFF IMPOSED BY HYDROLOGICAL BALANCE

The hydrological balance in the topographically closed Estancia basin, as expressed in the elevation of the water table, provides an alternative and independent means for constraining estimates of runoff under present and previous climatic conditions. In the late Pleistocene, for example, the water table (lake level) stood ~40 m above the general elevation of the modern valley floor (Allen & Anderson, 2000). Today, the water table is ~7 m below that same elevation. One way to assess the reasonableness of the SWAT estimate of modern runoff is to incorporate it into a comprehensive model of the basin that includes groundwater flow, surface runoff, and a lake. Lake growth or stabilization at some elevation above the basin floor would indicate a runoff estimate too high for modern climatic conditions. Lake desiccation, on the other hand, is to be expected, and the departure from modern conditions needed to make a lake rise in the basin may limit modern runoff estimates.

In order to further examine the total SWAT-generated streamflow value, this study made use of a ground- and surface-water flow model of the Estancia basin (ESTAN97) developed by Shafike & Flanigan (1999) and based on the groundwater program MODFLOW (McDonald & Harbaugh, 1988). The ESTAN97 model was developed to study the impact of future development on aquifer heads within the Estancia basin. The model was calibrated using predevelopment head values and previously published estimates of basin discharge and then used to simulate the aquifer drawdown that occurred after 1940 when agricultural irrigation accelerated in the basin. Under modern climate, Smith (1957) estimated that 6.2×10^7 m^3 $year^{-1}$ of groundwater discharges through the playas. In comparison, DeBrine (1971) estimated discharge at between 3.3×10^7 and 4.4×10^7 m^3 $year^{-1}$. Shafike & Flanigan (1999) chose a value in the middle of DeBrine's range (3.7×10^7 m^3 $year^{-1}$), and balanced it with streamflow from the Manzanos and general groundwater recharge. For streamflow, they used a value of 1.0×10^7 m^3 $year^{-1}$ based on the New Mexico State Engineer (1961) estimate of runoff in the Gallinas River basin analogue. General recharge (2.7×10^7 m^3 $year^{-1}$) was determined by subtracting this value of streamflow from the groundwater discharge value, and was then applied around the basin perimeter, with the highest MODFLOW cell values of recharge given to the high peaks of the Manzanos. Under these conditions, simulated heads closely matched (± ~4m) actual water levels at 10 different well sites throughout the basin, indicating that aquifer properties and volumes of recharge and discharge were well characterized by the model.

In the present study, ESTAN97 was modified to make use of the MODFLOW lake package LAK2 (Council, 1999), with the playa discharge zone in the centre of the basin replaced with lake cells and the stream package in MODFLOW modified to include streams that were active during the Late Pleistocene but that are dry today (Fig. 5). The topography of the basin was also changed to reflect the late Pleistocene lake floor. The same recharge values were used here, and, following the example of Shafike & Flanigan (1999), SWAT runoff delivered to the basin floor was placed at the top of MODFLOW stream reaches and allowed to flow toward the lake. Modern precipitation (350 mm year^{-1}) and evaporation (1200 mm year^{-1}) were applied to the lake surface, and the model was run for 100 years.

Under these hydrological conditions, and with the water table (lake surface) at a starting elevation of ~1860 m, the water level in the basin fell to the ~1845 m elevation of the late Pleistocene lake floor in fewer than 30 years of simulation (Fig. 6). Indeed, in order for the water level to rise above the elevation of the late Pleistocene lake floor, total runoff in the basin had to be increased at least five-fold, and even with this increased rate of runoff, the lake achieved a depth of only 2 m. An increase in runoff of nearly 15 times the modern estimate was necessary for the lake to stabilize at the elevation it occupied during relatively dry intervals reflected in late Pleistocene lowstands (1862 m).

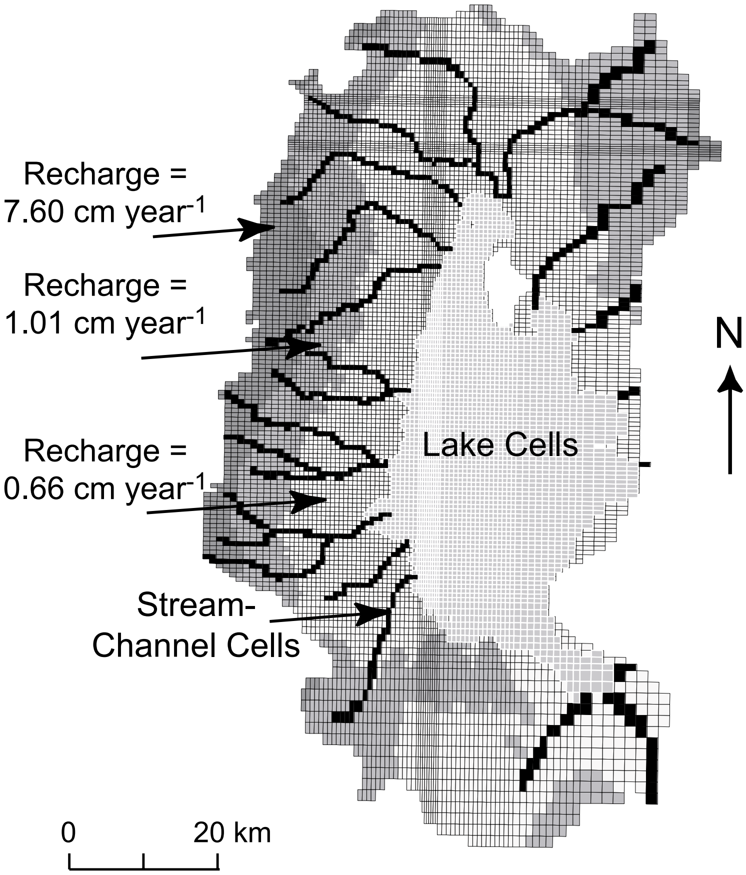

Fig. 5 Model grid for modified ESTAN97 model showing zones of recharge and stream and lake cells. Most groundwater recharge and runoff is at high to medium elevations along the western divide in the Manzano Mountains.

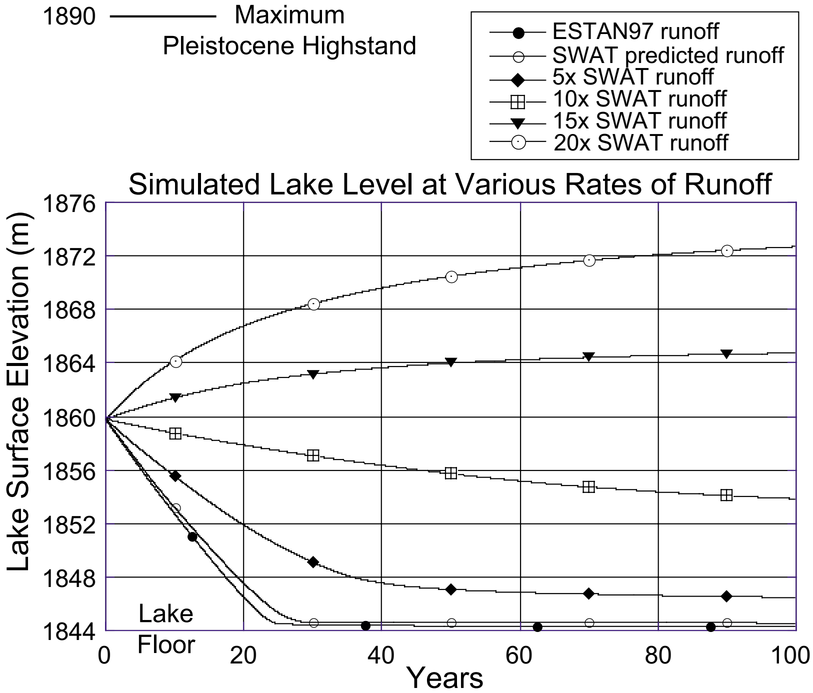

Fig. 6 Lake level predicted by ESTAN97 with the LAK2 package for different amounts of runoff. For all model runs, recharge is as specified by Shafike & Flanigan (1999), and precipitation on and evaporation from the lake surface are modern values (Leopold, 1951). Even though the SWAT model predicts runoff four times greater than that used by Shafike & Flanigan to calibrate ESTAN97, this inflow is insufficient to cause the lake to rise above the late Pleistocene basin floor.

The changes in precipitation necessary to cause increased runoff to the lake during the late Pleistocene would themselves have impacted lake water balance as well as rates of groundwater recharge, and the authors do not mean to suggest that late Pleistocene water levels were achieved by changes in runoff only. However, this analysis is useful in that it allows a general estimate of how much net inflow (made up of streamflow, groundwater, and direct precipitation on the lake surface minus evaporation) must be increased in order to support the late Pleistocene lake (~15×). This question has been a matter of great debate for Lake Estancia, as discussed by Galloway (1970) and Brakenridge (1978), who called on cooler temperatures of the late Pleistocene and a reduction in evaporation rates rather than on an increase in precipitation, as proposed by Leopold (1951), to generate the lake. Future experiments with the SWAT and modified ESTAN97 models will test these workers' climate scenarios to see which is most compatible with the known lake level history.

DISCUSSION AND CONCLUSIONS

With the exception of snowmelt factors, very few parameters required manipulation to achieve streamflow values within 30% of observational data and previous estimates. Factors that were changed included the creation of zones of mixed vegetation to match juniper-grassland assemblages found in the field. In addition, the AVSwat2000 interface routinely miscalculated values of heat units to maturity for several of the vegetation covers used in the model, so these values were calculated outside of the interface and manually entered into model input files. Other than these minor changes, nothing was required to generate the streamflow values shown in Fig. 4.

Confidence in the modelled Tajique runoff estimate is reinforced by results from the Torreon drainage, an area of similar size and character, and from the smaller Piños Reales drainage. However, the overestimate from Cañon Nuevo may point to the importance of accurate soils data. The same methods, when applied to all the sub-watersheds that drain the eastern flank of the Manzano Mountains yielded a runoff ~30% lower than a previously estimated value (New Mexico State Engineer, 1961), which is not an exceptional difference when one considers the assumptions made in the engineering report. The accuracy of streamflow estimates can be expected to decrease as one moves to drainage basins at lower elevations and in other parts of the Estancia basin. With no data for comparison, the model calibration parameters were extended for the eastern face of the Manzano Mountains to the northern, eastern, and southern parts of the Estancia basin where vegetation and soils are significantly different. As a result, one has less confidence in the runoff estimate for the entire basin (3.9×10^7 m^3 $year^{-1}$) than for the upper watersheds of the Manzano Mountains.

The aim of this investigation was to determine if the USDA SWAT model could be adapted to the Estancia basin for the eventual purpose of evaluating previously proposed late Pleistocene climate scenarios. The principal limitation, as expected, was not in the model itself, but in the absence of long and reliable records of streamflow, and to a lesser extent, of meteorological data, with which to calibrate. In the case of the Estancia basin, the limited data available allowed comparison of simulated and observed streamflow and permitted an approximate calibration of the SWAT model, which, it is estimated, generates streamflow values within 30% of observed values. If more data were available for calibration (as is true for some closed basins that contained Pleistocene lakes, such as the Owens Lake and the Silver Lake in California, or the Pyramid Lake in Nevada), more accurate estimates of modern runoff might be possible.

Uncertainties in the SWAT runoff model for the Estancia basin may be unacceptable in applications such as water resources and engineering, but the same information may be of considerable value in investigations of lake history and past climatic change. This possibility was explored by adapting a groundwater model to estimate total flow into and out of the closed Estancia basin and by expressing the hydrological balance in terms of water levels in the basin, as defined by shoreline evidence. It appears that annual inflow about five times higher than present would be needed to make even a shallow lake appear in the basin, and much larger changes in runoff and climate are inferred for the late Pleistocene highstands of Lake Estancia.

Even the large uncertainty of SWAT-estimated runoff in closed, arid basins may improve present estimates of past climate change. An advantage of having even a roughly calibrated physical runoff model such as SWAT that is linked to the climate variables of precipitation and temperature is in interactively evaluating combinations of runoff, precipitation, and temperature, as proposed in various climate scenarios. In this regard, the model appears to perform reasonably well over intervals of several years, and the results presented here suggest a wider application of SWAT or similar models in palaeohydrological investigations.

Acknowledgements The Lake Estancia research project was supported by National Science Foundation Grant EAR9631538. The authors gratefully acknowledge the help of Bruce Allen, Tom Loveland, and Amy Ellwein in field investigations, and the cooperation of Mike and Sue Harvey, Karl Barner, Jim McMath, and other ranch owners and operators in the Estancia Valley, as well as property owners in the Manzano Mountains, for access to places of investigation. Thanks are also due to Susan Neitsch, Nancy Sammons, and Mauro Di Luzio for assistance with SWAT and the AVSwat2000 interface, and to Frank Farquharson and Albert Rango for their comments, which helped us to improve the manuscript.

REFERENCES

Allen, B. D. (1993) Late Quaternary lacustrine record of paleoclimate from Estancia basin, New Mexico. PhD Dissertation, University of New Mexico, Albuquerque, New Mexico, USA.

Allen, B. D. & Anderson, R. Y. (2000) A continuous high-resolution record of late Pleistocene climate variability from Estancia basin, New Mexico. *Geol. Soc. Am. Bull.* **112** (9), 1444–1458.

Antevs, E. (1954) Climate of New Mexico during the last glacial-pluvial. *J. Geol.* **62**, 182–191.

Arnold, J. G., Williams, J. R., Srinivasan, R. & King, K. W. (1996) *SWAT: Soil and Water Assessment Tool*. USDA, Agricultural Research Service, Grassland, Soil and Water Research Laboratory, Temple, Texas, USA.

Beal, L. V. & Gold, R. L. (1987, 1988) (published annually) Water resources data, New Mexico, water year 1987. *US Geol. Survey Water-Data Report NM-87-1*.

Benson, L. V. & Paillet, F. L. (1989) The use of total lake-surface area as an indicator of climatic change: examples from the Lahontan basin. *Quatern. Res*. **32**, 262–275.

Bingner, R. L., Garbrecht, J., Arnold, J. G., & Srinivasan, R. (1997) Effect of watershed subdivision on simulation runoff and fine sediment yield. *Trans. Am. Soc. Agric. Engrs* **40**, 1329–1335.

Bourlier, B. G., Neher, R. E., Crezee, D. B., Bowman, K. J. & Meister, D. W. (1970) *Soil Survey, Torrance Area, New Mexico*. US Dept of Agriculture, Soil Conservation Service and Forest Service, in cooperation with New Mexico Agricultural Experiment Station. Available from Superintendent of Documents, US Govt Printing Office, Washington, DC 20402, USA.

Bradley, R. S. (1999) *Paleoclimatology,* second edn. Academic Press, New York, USA.

Brakenridge, G. R. (1978) Evidence for a cold, dry full-glacial climate in the American Southwest. *Quatern. Res*. **9**, 22–40.

Council, G. W. (1999) *A Lake Package for MODFLOW (LAK2): Documentation and User's Manual, Version 2.2*. HSI Geotrans, Sterling, Virginia, USA.

DeBrine, B. E. (1971) Quantitative hydrologic study of a closed basin with a playa (Estancia Valley, New Mexico). PhD Dissertation, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA.

Di Luzio, M., Srinivasan, R. & Arnold, J. G. (2002) Integration of watershed tools and SWAT model into BASINS. *J. Am. Water Res. Assoc*. **38**, 1127–1141.

Fontaine, T. A., Klassen, J. F., Cruickshank, T. S. & Hotchkiss, R. H. (2001) Hydrological response to climate change in the Black Hills of South Dakota, USA. *Hydrol. Sci. J.* **46**(1), 27–40.

Folks, J. J. (1975) *Soil Survey of Santa Fe Area, New Mexico*. USDA, Soil Conservation Service, and Forest Service and US Dept of the Interior, Bureau of Indian Affairs. Available from: Cartographic Division, Soil Conservation Service, US Dept of Agriculture, Washington, DC 20250, USA.

Galloway, R. W. (1970) The full-glacial climate in the southwestern United States. *Ann. Assoc. Am. Geographers* **60**, 245–256.

Hargreaves, G. H. & Samani, Z. A. (1985) Reference crop evapotranspiration from temperature. *Appl. Engng Agric.* **1**, 96–99.

King, K. W., Arnold, J. G. & Bingner, R. L. (1999) Comparison of Green-Ampt and curve number methods on Goodwin creek watershed using SWAT. *Trans. Am. Soc. Agric. Engrs* **42**, 919–925.

Leopold, L. B. (1951) Pleistocene Climate in New Mexico. *Am. J. Sci*. **249**, 152–168.

McDonald, M. G. & Harbaugh, A. W. (1988) A modular three-dimensional finite-difference ground-water flow model. *US Geol. Survey Techniques of Water-resources Investigations, Book 6*.

Menking, K. M., Anderson, R. Y., Brunsell, N. A., Allen, B. D., Ellwein, A. L., Loveland, T. A. & Hostetler, S. W. (2000) Evaporation from groundwater discharge playas, Estancia basin, central New Mexico. *Global Planet. Change* **25**, 133–147.

Neel, G. M. (1925) *Surface Water Supply of New Mexico.* Office of New Mexico State Engineer, Santa Fe, New Mexico, USA.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., Srinivasan, R. & Williams, J. R. (2002) *Soil and Water Assessment Tool User's Manual, Version 2000*. GSWRL Report 02-02, BRC Report 02-06, Texas Water Resources Institute TR-192, College Station, Texas, USA.

New Mexico State Engineer (1961) Report of reconnaissance survey, dam and reservoir sites, east slope of Manzano Mountains, Bernalillo and Torrance Counties, New Mexico. *New Mexico State Engineer Open-file Report.*

NOAA (National Oceanic and Atmospheric Administration) (annual series) Climatological data annual summary, New Mexico. National Climatic Data Center, Asheville, North Carolina, USA.

Rosenberg, N. J., Epstein, D. L., Wang, D., Vail, L., Srinivasan, R. & Arnold, J. G. (1999) Possible impacts of global warming on the hydrology of the Ogallala aquifer region. *Climatic Change* **42**, 677–692.

SCS (Soil Conservation Service) (1972) *National Engineering Handbook,* Sec. 4: *Hydrology*. US Dept Agric. US Govt Printing Office, Washington, DC, USA.

Shafike, N. G. & Flanigan, K. G. (1999) Hydrologic modeling of the Estancia basin, New Mexico. In: *New Mexico Geological Soc. Guidebook, 50th Field Conference*, *Albuquerque Geology*, 409–418. New Mexico Geological Society, Socorro, New Mexico, USA.

Smith, G. I. & Street-Perrott, F. A. (1983) Pluvial lakes in the western United States. In: *Late Quaternary Environments of the United States* (ed. by H. E. Wright, Jr), 190–211. University of Minnesota Press, Minneapolis, USA.

Smith, R. E. (1957) Geology and ground-water resources of Torrance County, New Mexico. *Ground-Water Report no. 5*, *New Mexico State Bureau of Mines and Mineral Resources*. Socorro, New Mexico, USA.

Stone, M. C., Hotchkiss, R. H., Hubbard, C. M., Fontaine, T. A., Mearns, L. O. & Arnold, J. G. (2001) Impacts of climate change on Missouri River basin water yield. *J. Am. Water Resour. Assoc*. **37**, 1119–1129.

Stonefelt, M. D., Fontaine, T. A. & Hotchkiss, R. H. (2000) Impact of climate change on water yield in the upper Wind River basin. *J. Am. Water Resour. Assoc*. **36**, 321–336.

Thompson, B. C., Crist, P. J., Prior-Magee, J. S., Deitner, R. A., Garber, D. L. & Hughes, M. A. (1996) Gap analysis of biological diversity conservation in New Mexico using geographic information systems. Final Gap Analysis Report, US Dept of the Interior, New Mexico Cooperative Fish and Wild. Res. Unit, Las Cruces, New Mexico, USA.

Tuan, T., Everard, C. E., Widdison, J. G. & Bennett, I. (1973) *The Climate of New Mexico*. New Mexico State Planning Office, Santa Fe, New Mexico, USA.

US Department of Agriculture Weather Bureau (1915–1919) (published monthly) *Climatological Data.* Weather Bureau Office, New Mexico Section, Denver, Colorado, USA.

White, R. R. (1994) Hydrology of Estancia basin, central New Mexico. *US Geol. Survey, Water-resources Investigations Report 93-4163.*

Received 17 September 2002; accepted 11 August 2003